ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An UGC Approved Journal)

Website: www.ijareeie.com

Vol. 6, Issue 8, August 2017

Simulation of Islanding Detection Using PLL in Three-Phasegrid-Interface Power

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ABSTRACT: Phase locked loop and synchronization techniques are one of the most important issues for operating grid-interfaced converters in practical applications, which involve Distributed Power Generation Systems, Flexible AC Transmission Systems (FACTS), and High Voltage Direct Current (HVDC) Transmission, and so on.This paper proposes a systematic PLL modeling anddesign approach to evaluate different frequency-based islandingdetection methods. Two different types of PLL-based islandingdetection solution are discussed, accounting for a majority ofthe existing methods. The first method is to modify the PLL toconstantly move the stable equilibrium point. The second methodis to modify the PLL small-signal characteristics to achieve amonotonic instability behavior under the islanded conditions.The design procedures of these methods are presented using theproposed PLL modeling approach.

KEYWORDS: Converter stability, distributed generation (DG), islanding detection, phase-locked loop (PLL).

I. INTRODUCTION

Distributed generation for renewable energy sources is penetrating theelectric power system due to the rising cost of traditional energy sources andthe environmentally friendly features of renewable energy. Over 60countries around the world have set targets for renewable energy supply [1].The types of renewable energy include solar, wind, hydrogen, biomass,geothermal, hydropower, and biodiesel. Many of these renewable energysources are designed to supply energy into the electric power system.Each power electronics interface should provide quality power to theelectric grid for the loads. This means the harmonics should be low, theinverter should be turned off if the voltage or frequency goes out of range,and the inverter should be able to detect when the centralized generator is nolonger connected; this case is called unintentional islanding. An island mayoccur for many reasons;

such as, a disconnection for servicing, human error,an act of nature, or one of the circuit breakers in the power system trips asshown in Fig. 4 with distributed generation (DG). Under the islandcondition, the distributed resource (DR) is required to disconnect within 2seconds according to IEEE 1547[2]-[3]. A distributed resource shoulddisconnect from the electric grid for many reasons: to prevent the electricpower grid from reconnecting with the distributed resource out of phasecausing a large spike in voltage damaging the loads, a line worker could gethurt, and the utility is liable for power lines even when distributed resourcesuse them to transmit power.
Besides the detection of abnormal grid conditions, the standard also requires that a DG unit has to detect the unintentionalislanding condition and de-energizes the area electric powersystem (EPS) within 2 s. When this condition occurs, thesystem voltage and frequency normally shift out of the normalrange and an over or under voltage (OUV) or frequency (OUF)protection method can be directly used to detect the islandingevent. However, the detection time might be longer than2 s if the voltage or frequency shifts two slow or does notshift at all under certain local loading conditions. Therefore,a sensitive but reliable islanding-detection algorithm has tobe implemented in any DG units to ensure the fulfillment ofunintentional islanding-detection requirements.In addition to detecting the grid faults, islanding-detectionalgorithms play another key role in ac microgrid and nanogridsystems. Through the detection of islanding event, these methods allow the control system to precisely decide an appropriateoperational mode accordingly.Many islanding-detection algorithms have been proposed inthe literature. In general, the islanding detection can adopteither passive or active methods [4]–[7]. Passive methodsare simple but susceptible to nondetection

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zones (NDZ) andincompatible to certain grid codes, such as low- or zerovoltage ride-through (LVRT or ZVRT) requirements. Activemethods introduce continuous perturbations and may distortthe converter's output in the case of current perturbation.The performance of active detection methods varies from theoperation conditions, and a large perturbation could lead topower quality and system instability concerns. Frequencybased islanding-detection methods are gaining popularityrecently as the method itself does not violate the LVRTrequirement.

Therefore, it is necessaryand also our intention to investigate the inherent mechanismand the converter output frequency dynamic behaviors usinga systematic approach, which can be eventually applied tomultiple-inverter conditions.This paper is dedicated to the modeling and design procedures for frequency-based islanding detection.

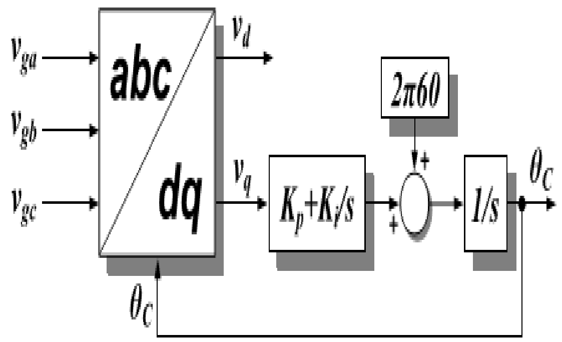

Fig. 1. Synchronous reference frame PLL linear model.

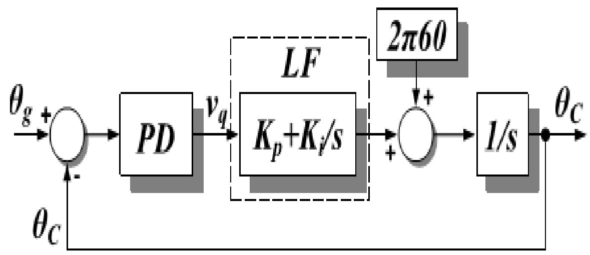

Fig. 2.Typical PLL linear model.

Two typesof PLL-based islanding detection methods will be discussedand compared with the typical PLL. Figs. 1 and 2 show thetypical SRF PLL structure and its linear model. The closedloop response is shown in (1), where the phase-detectorgain kPD equals the input ac voltage amplitude V_g.

II. ISLANDING DETECTION BASED ON PLLLARGE-SIGNAL STABILITY

Fig. 3 shows a three-phase power converter system whereZ_L and Z_g are the paralleled RLC local load and gridimpedances, respectively. The islanding event occurs whenthe point-of-common-coupling (PCC) switch opens. I_c is theinjection current amplitude of the inverter.The modeling of PLL frequency behavior at the islandedcondition was presented in [5]. In most cases,the islanding events would be effectively detected by directlymonitoring the PLL output frequency. However, for the paralleled RLC load with 60 Hz resonant frequency, the PLLoutput frequency will stay at the resonant frequency and thesystem cannot detect the islanding event. Therefore, the PLL orinternal control loops are usually modified to detect islandingunder such a loading condition.

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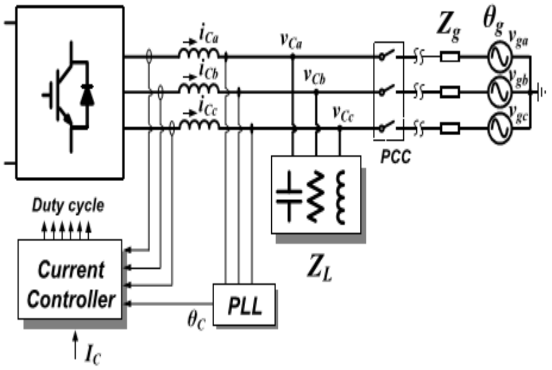

Fig. 3.Three-phase grid-interface power converter system.

The nonlinear PLL modelunder the islanded condition is shown in Fig. 4. Under theislanded condition, the PLL still tracks the inverter terminalvoltage produced by the inverter's current flowing to Z_L.Therefore, there is a self-synchronization loop shown in themodel.

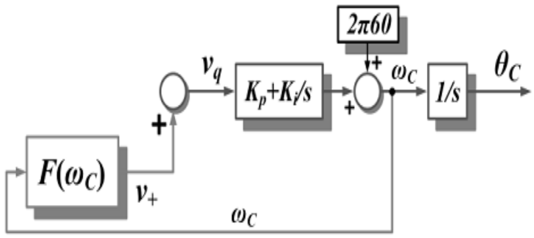

Fig. 4.SRF PLL model under the islanded condition.

This nonlinear PLL model can be linearized around the linefrequency to obtain the small-signal model [5], as shown in Fig. 5. I_cR_L is considered as k_{PD}.

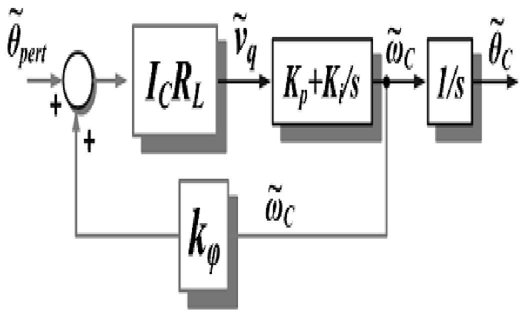

Fig.5.Linearized small-signal PLL model under islanded condition.

If the equilibrium point changes, the PLL output will automatically react to this change. Therefore, many islanding-detectionmethods are proposed to actively perturb the equilibrium point.Fig. 6 shows an example of PLL-based islanding detectionusing such a way.An additional large-signal feedback loop is introduced andmultiplied by a gain k_{pt} (a 0.5 or 1 Hz small triangular signalbetween 0 and k_{max}). This additional feedback loop constantlyshifts the equivalent resonant frequency. Thus, the PLL outputfrequency will keep moving all the time.

As shown in Fig. 7, the output frequency will follow theinput injection signal k_{pt}. Eventually, the average value ω_{av} ofthe PLL output will stay lower than 60 Hz to ensure F = 0.

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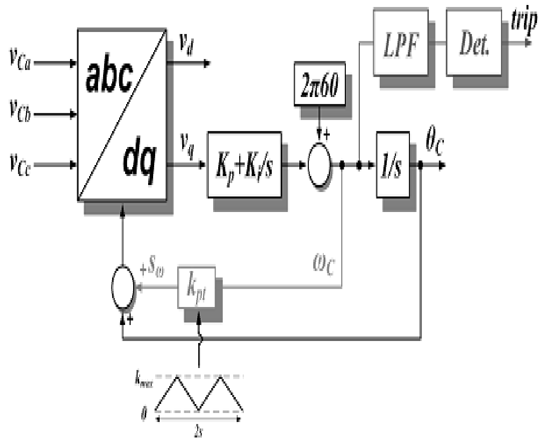

Fig. 6.Modified PLL with a large-signal feedback for islanding detection.

According to Fig. 7, the PLL output ω_C can be directlymonitored to detect the islanding condition, and a low-passfilter (LFP) is used to eliminate the high-frequency noise.
The islanding-detection protection signal is set when ω_C islower than the ωth or the variation range of ω_C is beyond thethreshold.The only design parameter is kpt, because it is a very lowfrequency signal, much lower than the PLL bandwidth. Theoutput of the PLL can be assumed to be at the steady state allthe time.

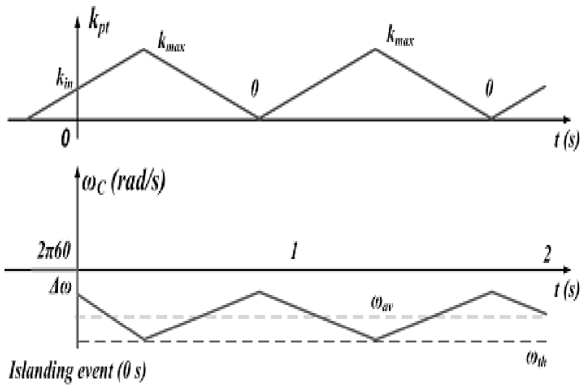

Fig. 7. First PLL output behavior when the islanding condition occurs.

The change of the grid synchronization performance owingto the additional feedback loop can be investigated by exploring the PLL model at the stiff grid-tied mode, as shownin Fig. 9.

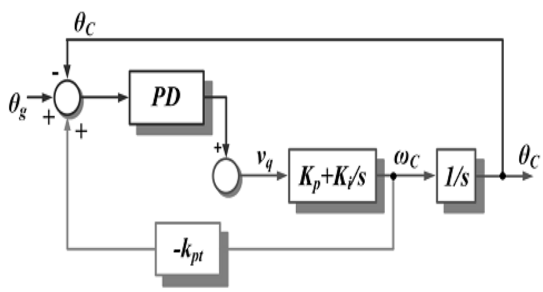

Fig. 9.Modified PLL model under the stiff grid-connected condition.

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III. ISLANDING DETECTION BASED ON PLLSMALL-SIGNAL STABILITY

The PLL cannot detect the paralleled RLC load, becausethe PLL is stable according to (5). Therefore, the equilibriumpoint itself can be modified to be unstable. With this idea, thePLL can be modified as shown in Fig. 15. An additional smallsignal feedback term is introduced with a constant gain N.Then, the equivalent small-signal PLL model aroundthe equilibrium point at the islanded condition is shown
in Fig. 16

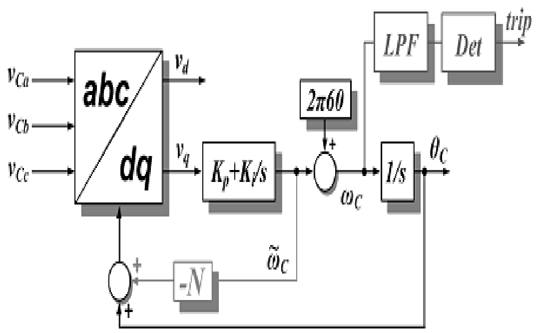


Fig. 15. Modified PLL with a small-signal feedback for islanding detection.

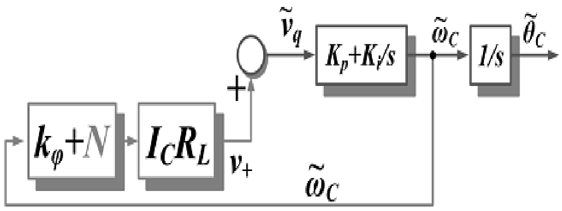
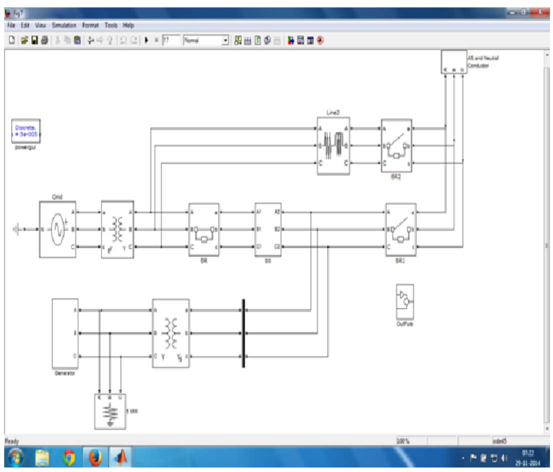


Fig. 16. Small-signal model of the modified PLL for islanding detection.

IV. SIMULATION RESULTS

The PLL behavior is verified in a 2.5 kW two-level three-phase PWM converter system shown below



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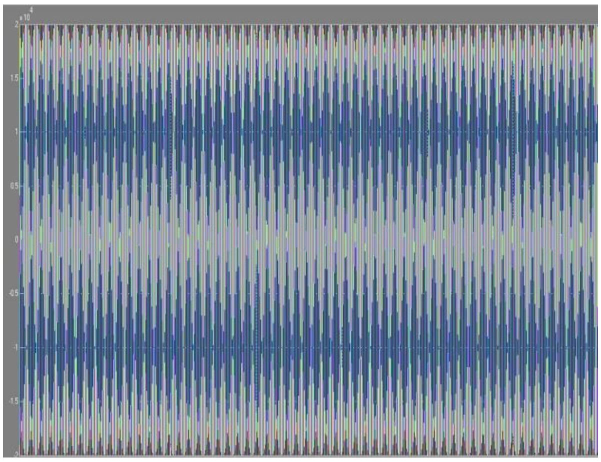

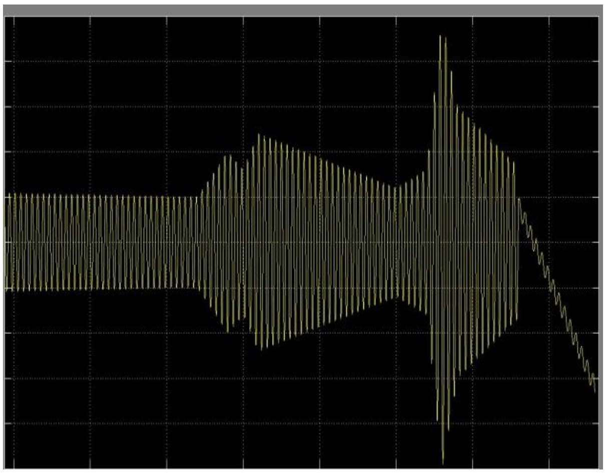

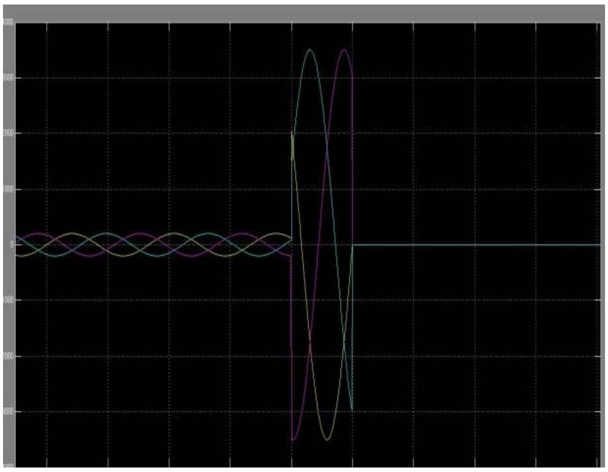

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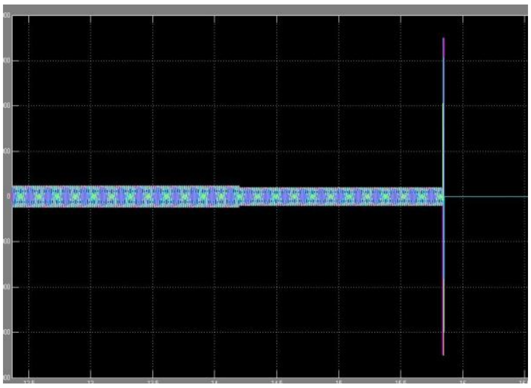

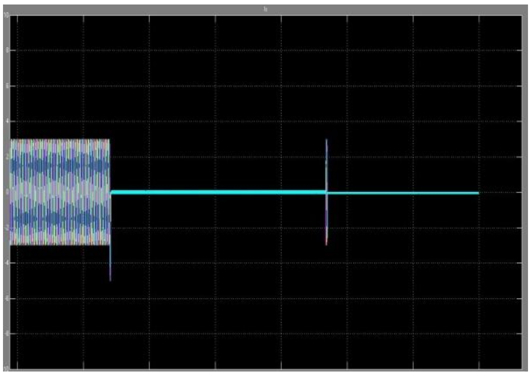

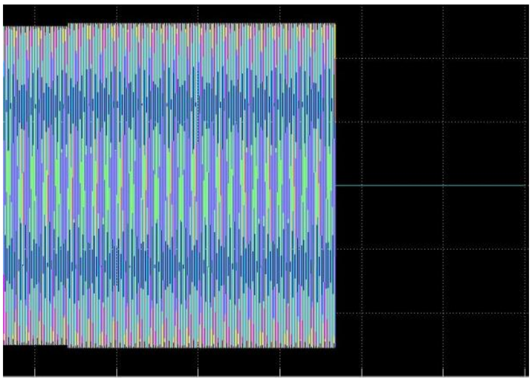

V. CONCLUSION

The proposed PLL model can be used to analyze and explain the underlying theory for both large-signalperturbation-based and small-signal positive-feedback-basedislanding-detection solutions. For the large-signal perturbationbased method, the PLL keeps tracking the constantly movingequilibrium point. The change of PLL's grid synchronizationperformance is very limited and is robust in grid-tied conditions. The detection speed is inherently slow due to the slowPLL bandwidth, thereby requiring a low-frequency, for example, 1 Hz, signal injection. For the small-signal instabilitybased method, the proposed small-signal PLL model showsthat the additional small-signal loop gain design is determined by the local load power quality factor and its resonantfrequency to ensure islanding-detection performance.

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